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Critical review of heat transfer characteristics of nanofluids

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Abstract

Researches in heat transfer have been carried out over the previous several decades, leading to the development of the currently used heat transfer enhancement techniques. The use of additives is a technique applied to enhance the heat transfer performance of base fluids. Recently, as an innovative material, nanometer-sized particles have been used in suspension in conventional heat transfer fluids. The fluids with these solid-particle suspended in them are called 'nanofluids'. The suspended metallic or nonmetallic nanoparticles change the transport properties and heat transfer characteristics of the base fluid. The aim of this review is to summarize recent developments in research on the heat transfer characteristics of nanofluids for the purpose of suggesting some possible reasons why the suspended nanoparticles can enhance the heat transfer of conventional fluids and to provide a guide line or perspective for future research.

Keywords: Nanofluid; Nanoparticle; Suspension; Heat transfer enhancement

Contents

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1. Introduction

Conventional fluids, such as water, engine oil and ethylene glycol are normally used as heat transfer fluids. Although various techniques are applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Improving of the thermal conductivity is the key idea to improve the heat transfer characteristics of conventional fluids. Since a solid metal has a larger thermal conductivity than a base fluid, suspending metallic solid fine particles into the base fluid is expected to improve the thermal conductivity of that fluid. The enhancement of thermal conductivity of conventional fluids by the suspension of solid particles, such as millimeter- or micrometer-sized particles, has been well known for more than 100 years [1]. However, they have not been of interest for practical applications due to problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel. The recent advance in materials technology has made it possible to produce nanometer-sizes particles that can overcome these problems. Innovative heat transfer fluids-suspended by nanometer-sized solid particles are called 'nanofluids'. This suspended nanoparticles can change the transport and thermal properties of the base fluid. The aim of this paper is to present a review of the open literature describing recent developments in the enhancement of heat transfer by using nanofluids. In Section 2, the preparation of nanofluids is described. In the following sections, an overview of recent experimental works on thermal properties, the heat transfer performance, and the proposed theoretical investigations of nanofluids is given. In Section 7, some concluding remarks and future expectations are discussed.

2. Preparation of nanofluids

A liquid suspended with particles of nanometer dimension is termed a nanofluid. The nanoparticles were used to produce nanofluids in the reviewed literature are: aluminum oxide (Al_2O_3), copper (Cu), copper oxide (CuO), gold (Au), silver (Ag), silica nanoparticles and carbon nanotube. The base fluids used were water, oil, acetone, decene and ethylene glycol. Nanoparticles can be produced from several processes such as gas condensation, mechanical attrition or chemical precipitation techniques [1]. Gas condensation processing has an advantage over other techniques. This is because the particles can be produced under cleaner conditions and its surface can be avoided from the undesirable coatings. However, the particles produced by this technique occur with some agglomeration, which

can be broken up into smaller clusters by supplying a small amount of energy [1]. The preparation of a nanofluid begins by direct mixing of the base fluid with nanoparticles. The delicate preparation of a nanofluid is important because nanofluids need special requirements such as an even suspension, durable suspension, stable suspension, low agglomeration of particles, and no chemical change of the fluid [2]. Xuan and Li [2] suggested methods used for stabilizing the suspensions: (1) changing the pH value of suspension, (2) using surface activators and/or dispersants, (3) using ultrasonic vibration. These methods can change the surface properties of the suspended particles and can be used to suppress the formation of particle clusters in order to obtain stable suspensions. The use of these techniques depends on the required application of the nanofluid. Selection of suitable activators and dispersants depends mainly upon the properties of the solutions and particles.

Particles can fracture or agglomerate after mixing into liquid. Transmission electron microscopy (TEM) is widely used to observe the characteristics of particles before and after dispersion in liquid. Some researchers [2–5] used ultrasonic vibration techniques to disperse the particles in the base liquid. However, the ultrasonic vibration can break the agglomerates as indicated in experiments of Das et al. [3–5]. While Xuan and Li [2] selected laurate salt and oleic acid as the dispersant to enhance the stability of the suspension, some researchers [1,3–5] did not use any dispersants to stabilize the suspension. The reasons for this were that the addition of the dispersant could influence the thermal conductivity of the base fluid itself, and thus, the real enhancement by using nanoparticles could be overshadowed.

3. Thermal conductivity of nanofluids

3.1. Experimental Investigations

Thermal conductivity is an important parameter in enhancing the heat transfer performance of a heat transfer fluid. Since the thermal conductivity of solid metals is higher than that of fluids, the suspended particles are expected to be able to increase the thermal conductivity and heat transfer performance. Many researchers have reported experimental studies on the thermal conductivity of nanofluids. The transient hot wire method, temperature oscillation and the steady-state parallel plate method has been employed to measure the thermal conductivity of nanofluids. However, the transient hot wire method has been extensively used. The transient hot wire technique works by measuring the temperature/time response of the wire to an abrupt electrical pulse. The wire is used as both heater and thermometer. A derivation of Fourier's law and temperature data were used to calculate the thermal conductivity. The results from all of the available experimental studies indicated that nanofluids containing a small amount of nanoparticles have substantially higher thermal conductivity than those of base fluids.

Al_2O_3 and CuO are the most well-known nanoparticles used by many researchers in their experimental works. Even when the size of the particles and type of base fluids are different, all the experimental results showed the enhancement of the thermal conductivity.

Lee et al. [1] measured the thermal conductivity of nanofluids. The number-weighted particle diameter and the area weighted particle diameter used were 18.6 and 23.6 nm for CuO, and 24.4 and 38.4 nm for Al_2O_3, respectively. These particles were used with two

different base fluids: water and ethylene glycol to get four combinations of nanofluids (CuO in water, CuO in ethylene glycol, Al_2O_3 in water and Al_2O_3 in ethylene glycol). The nanofluids showed substantially higher thermal conductivities than those of the same liquids without the nanoparticles. The thermal conductivity of suspended CuO in ethylene glycol showed an enhancement of more than 20% at 4% volume fraction of nanoparticles. The thermal conductivity ratios increased almost linearly with an increase in volume fraction. The experimental results revealed that the thermal conductivity of nanofluids was dependent on the thermal conductivity of both the particles and the base fluids.

Wang et al. [6] used the steady-state parallel-plate technique to measure the thermal conductivity of nanofluids containing Al_2O_3 and CuO nanoparticles. The particles were dispersed in water, ethylene glycol, vacuum pump oil and engine oil. Experimental data showed that the thermal conductivity of all nanofluids were higher than those of their base fluids. The thermal conductivity of the nanofluids increased with increasing volume fraction of the nanoparticles. For a specific volume fraction, the increase of thermal conductivity was different for each base fluid.

Xuan and Li [2] presented a study on the thermal conductivity of a nanofluid consisting of copper nanoparticles and base liquid. The measured data showed that the suspended nanoparticles obviously increased the thermal conductivity of the base liquid. Thermal conductivity of the nanofluid increased with increasing volume fraction of nanoparticles. The ratio of thermal conductivity of Cu–water to that of the base liquid increased from 1.24 to 1.78 when the volume fraction of the nanoparticles varied from 2.5 to 7.5%.

Eastman et al. [7] reported an experimental study on the thermal conductivity of ethylene glycol-based nanofluids containing copper nanoparticles. The nanofluid exhibited an anomalously increased effective thermal conductivity. The thermal conductivity increased up to 40% for nanofluids consisting of 0.3% (by volume) of Cu nanoparticles of a mean diameter less than 10 nm dispersed in ethylene glycol.

Xie et al. [8] measured the thermal conductivity of Al_2O_3 nanoparticle suspensions. The effects of the pH value of the suspension, the specific surface area (SSA) of the dispersed Al_2O_3 particles, the crystalline phase of the solid phase, and the thermal conductivity of the base liquid on the enhanced thermal conductivity ratio were investigated. The addition of nanoparticles into the fluid led to higher thermal conductivity. The enhanced thermal conductivity increased with an increase in the volume fraction of Al_2O_3. The enhancement increased with an increase in the difference between the pH value and isoelectric point of Al_2O_3. For the suspensions containing the same base liquid, the thermal conductivity enhancements were highly dependent on the specific surface area (SSA) of the nanoparticles. For the suspensions using the same nanoparticles, the enhanced thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid. While, the crystalline phase of the nanoparticles did not appear to have any obvious effect on the thermal conductivity of the suspensions.

Das et al. [5] presented investigations on the increase of thermal conductivity with temperature of Al_2O_3 and CuO water-based nanofluids. In their study, a temperature oscillation technique was used to measure the thermal conductivity. The volume weighted average values of particle diameters was 38.4 nm for Al_2O_3 while that was 28.6 nm for CuO. The experimental results showed that the thermal conductivity increased with an increase in temperature. Nanofluids containing smaller particles (CuO) showed greater

enhancements of thermal conductivity with temperature than larger particles (Al_2O_3). The stochastic motion of nanoparticles could be a probable explanation of the thermal conductivity enhancement. This is because smaller particles are more easily to mobilise and bring out a higher level of stochastic motion.

Similar behavior was observed in the study by Patel et al. [9]. The effects of the size of particles, temperature, and chemical characteristics of particle coatings on thermal conductivity of nanofluids were presented. Gold (Au) and silver (Ag) nanoparticles with two kinds of coating, thiolate and citrate, were used in this experiment with water- and toluene-based fluids. Comparatively, the thermal conductivities of the nanofluids were higher than those of their base fluids. The increments in thermal conductivity of the nanofluids were found to be polynomial with temperature and almost linear with particle concentrations. These experiments indicated that the increase in the particle surface area per unit volume of nanofluid could explain the phenomenon of thermal conductivity enhancement. Although silver particles had higher thermal conductivity and concentration, the thermal conductivity enhancement of the silver nanofluids were less than that of the gold nanofluids. This is because the silver particle sizes in these experiments were larger than the gold particles. The nanofluids with particles with thiolate coating had less thermal conductivity enhancement than those with particles with citrate coating. This showed that the effective heat transfer at metal surface contact was decided by the type of coating.

The thermal conductivity of nanofluids containing carbon nanotubes was measured by Choi et al. [10] and Xie et al. [11]. Choi et al. [10] measured the thermal conductivity of carbon nanotube–oil mixture at room temperature. The thermal conductivity enhancement ratio was more than 2.5 at approximately 1 vol.% of nanotube concentration. In work by Xie et al. [11], carbon nanotube was dispersed in distilled water, ethylene glycol and decene. The same results were observed; nanofluids containing a small amount of carbon nanotubes had significantly higher thermal conductivities than their base liquids. The thermal conductivity of the nanofluids was nonlinear with concentration and apparently with higher nanotube concentrations. The thermal conductivity enhancement increased with increasing nanotube concentrations but reduced with increasing thermal conductivity of the base fluids. The size and shape of nanotube play key roles in the nonlinear phenomenon. Comparatively, with other nanostructure materials, nanotubes provided the highest thermal conductivity enhancement.

3.2. Analytical investigations

As is evident from the work of many researchers, the thermal conductivity of nanofluids increased as a function of thermal conductivity of both the base fluid and the nanoparticle material, the volume fraction, the surface area, and the shape of the nanoparticles suspended in the liquid. There are no theoretical formulas currently available in open literature for predicting the thermal conductivity of nanofluids. The Maxwell model, an existing traditional model for thermal conductivity, was proposed for solid–liquid mixtures with relatively large particles. Many later proposed models have been based on the Maxwell model. The effective thermal conductivity, k_{eff} is

$$k_{\text{eff,Maxwell}} = \frac{k_{\text{p}} + 2k_1 + 2(k_{\text{p}} - k_1)\phi}{k_{\text{p}} + 2k_1 - (k_{\text{p}} - k_1)\phi}\, k_1$$

where k_p is the thermal conductivity of the particle, k_1 is the thermal conductivity of the liquid and ϕ is the particle volume fraction of the suspension. Maxwell's model shows that the effective thermal conductivity of suspensions depending on the thermal conductivity of spherical particle, base liquid and the volume fraction of the solid particles.

For non-spherical particles, the thermal conductivity of the nanofluids depends not only on the volume fraction of the particles, but also on the shape of the particles [1]. Hamilton and Crosser developed a model for the effective thermal conductivity of two-component mixtures. The model is a function of the conductivity of both the particle and base fluid, and the shape of the particles. The thermal conductivity of two-component mixtures, in which the ratio of conductivity of two phases is larger than 100, can be determined from [1] as follows;

$$k_{\text{eff,Hamilton}} = \frac{k_p + (n-1)k_1 - (n-1)(k_1 - k_p)\phi}{k_p + (n-1)k_1 + (k_1 - k_p)\phi} k_1$$

where n is the empirical shape factor given by $n = 3/\psi$ and ψ is the sphericity, defined by the ratio of the surface area of a sphere, having a volume equal to that of the particle, to the surface area of the particle.

Xuan and Li [2] used the Hamilton–Crosser model to obtain a rough estimation of the thermal conductivity of the nanofluids for different values of ψ from 0.5 to 1.0. The data showed that the model results for $\psi = 0.7$ were close to their experimental data. Lee et al. [1] pointed out that the thermal conductivity ratios for $\psi = 1$ (spherical particles) calculated from this model was in good agreement with their Al_2O_3 nanofluids experimental results. However, this model was not suitable for predicting the thermal conductivity of CuO nanofluids.

Keblinski et al. [12] proposed a comprehensive explanation of four possible factors to understand the mechanism of heat transfer in nanofluids, which were the Brownian motion of particles, molecular-level layering of the liquid at the interface between liquid and particle, the nature of heat transport in the nanoparticles, and the effects of nanoparticle clustering. This study led to the conception for predicting thermal conductivity of nanofluids. The investigation demonstrated that the movement of nanoparticles due to Brownian motion is very slow in transporting significant amounts of heat through a nanofluid. The presence of layering of liquid at the liquid/particle interface brings a higher thermal conductivity of the nanofluid. Corresponding with the effect of particle size, a high layer thickness is more effective in the enhancement of thermal conductivity when the particle size is small. The nature of heat transport in the nanoparticle is of a ballistic manner rather than diffusive. The clustering of particles caused a negative effect on thermal conductivity enhancement. The thermal conductivity enhancement of loosely packed clusters is higher than that of closely packed clusters.

Wang et al. [13] proposed a fractal model for predicting the thermal conductivity of nanofluids based on the effective medium approximation and the fractal theory. The thermal conductivity can be calculated as:

$$k_{\text{eff,Wang}} = \frac{(1-\phi) + 3\phi \int_0^\infty \dfrac{k_{\text{cl}}(r)n(r)}{k_{\text{cl}}(r) + 2k_1}\,\mathrm{d}r}{(1-\phi) + 3\phi \int_0^\infty \dfrac{k_{\text{cl}}n(r)}{k_{\text{cl}}(r) + 2k_1}\,\mathrm{d}r} k_1$$

where $k_{\text{cl}}(r)$ is the thermal conductivity of particle clusters and $n(r)$ is the radius distribution function. With considering the effect of size and surface adsorption of

nanoparticles, the proposed model compared well with their experimental data for 50 nm CuO particles suspended in deionized water with particle concentrations lower than 0.25 vol.%.

Xue [14] proposed a model for predicting the thermal conductivity of nanofluids. The model developed was based on the Maxwell theory and average polarization theory, and on the assumption that there is an interfacial shell between the nanoparticles and liquid, and all nanoparticles are of the same rotational ellipsoid. The results from this model were compared with experimental data of Choi et al. [10] for carbon nanotube/oil nanofluid and Xie et al. [8] for Al_2O_3 nanoparticle–water nanofluid. The predictions were in good agreement with the experimental data for the same assumed interfacial shell thickness of 3 nm, but different for their thermal conductivity of the interfacial shell. However, the reasons for using the assumed values of thickness and thermal conductivity of the interfacial shell were not explained.

An alternative expression for calculating the effective thermal conductivity of solid–liquid mixtures was introduced by Yu and Choi [15]. They proposed that a structural model of nanofluids might consist of a bulk liquid, solid nanoparticles and solid-like nanolayers. The solid-like nanolayer act as a thermal bridge between a solid nanoparticle and a bulk liquid [15]. The formula yields:

$$k_{\mathrm{eff,Yu}} = \frac{k_{\mathrm{p}} + 2k_1 + 2(k_{\mathrm{p}} - k_1)(1+\beta)^3\phi}{k_{\mathrm{p}} + 2k_1 - (k_{\mathrm{p}} - k_1)(1+\beta)^3\phi}\, k_1$$

where β is the ratio of the nanolayer thickness to the original particle radius and k_{pe} is the equivalent thermal conductivity of the equivalent particle. In this model, the prediction is most effective when the nanoparticles have a diameter less than 10 nm.

Another new model for predicting thermal conductivity of nanofluids was proposed by Jang and Choi [16]. The fundamental role of dynamic nanoparticle was accounted for predicting thermal conductivity that considered four modes of energy transport in the nanofluid. They are: the collision between base fluid molecules, the thermal diffusion of nanoparticles in the fluid, the collision between nanoparticles due to Brownian motion, and the thermal interactions of dynamic nanoparticles with base fluid molecules. As with the results discussed in Keblinski et al. [12], it was found that the Brownian motion had less effect than the other modes and could be neglected. This is because the collision of nanoparticles due to Brownian motion is a very slow process. The expression is:

$$k_{\mathrm{eff,Jang}} = k_1(1-\phi) + k_{\mathrm{p}}\phi + 3C\,\frac{d_1}{d_{\mathrm{p}}}\,k_1 Re_{d_{\mathrm{p}}}^2 Pr\phi$$

where $Re_{d_{\mathrm{p}}}$ is the Reynolds number defined by $Re_{d_{\mathrm{p}}} = (\bar{C}_{\mathrm{RM}} d_{\mathrm{p}})/v$, C is a proportional constant, $\bar{C}_{\mathrm{RM}}$ is the random motion velocity of nanoparticles, v is the dynamic viscosity of base fluid, Pr is Prandtl number. The predictions from this model were in agreement with experimental data of Lee et al. [1], Eastman et al. [7] and Das et al. [3].

4. Boiling heat transfer

As mentioned before, the enhancements of thermal conductivity of nanofluids make them attractive for cooling applications. While using nanofluids for cooling at high heat flux applications, the heat transfer process follows the boiling regime. As nanoparticles increase

the thermal conductivity of conventional fluids, many researchers expected that nanoparticles would also have a reasonable potential to enhance the boiling heat transfer. This motivation brought out several experimental studies on the pool boiling characteristics of nanofluids.

In the work of Das et al. [3,4], experiments were carried out to evaluate pool boiling with nanofluids of 1, 2 and 4% of Al_2O_3 nanoparticle concentrations in water. The effects of particle concentration, heater diameter, and surface roughness of the heater on the boiling characteristic of nanofluids were studied. The presented results were somewhat contrary to expectations; nanofluids were expected to enhance the heat transfer characteristic during pool boiling. However, the boiling curves of nanofluids indicated that the boiling performance of the water deteriorated with the addition of nanoparticles, since the boiling curves were shifted to the right. The shift of the curves was proportional to the particle concentration and dependent on the tube roughness, and the deterioration of the heat transfer performance was stronger with smoother surfaces.

From the works by Das et al. [3,4], the nanoparticles deteriorated the boiling characteristics of water in the nucleate boiling regime. But it can be pointed out that their experiments were not tested until the critical heat flux limit was reached. You et al. [17] investigated an experimental study to find the boiling curve and critical heat flux in pool boiling from a flat square polished copper heater immersed in Al_2O_3–water nanofluid. Various nanoparticles volume fraction of Al_2O_3 ranging between 0.001 and 0.05 g/l were tested and compared with pure water. In the nucleate boiling regime of the boiling curves of nanofluids, the heat transfer enhancement or degradation were not observed. However, the critical heat fluxes of nanofluids were extremely increased. The increasing of critical heat flux was about 200% higher than pure water when the particles volume fractions were greater than 0.005 g/l. However, in this experiment the size of nanoparticles was not specified. Another experiment that confirms the increasing critical heat flux of nanofluids was investigated by Vassallo et al. [18] who observed the boiling characteristic of silica–water nanofluids with 0.5% volume concentration. The same tests were conducted for both nano- and micro-solutions at the same concentration compared to water. From boiling curves data, any heat transfer enhancement of nanofluids were not observed in the nucleate boiling regime, but the critical heat flux was markedly increased for both nano- and micro-particles. Addition of nanoparticles leaded to a maximum heat flux of about three times that of pure water and almost twice that of water with micro-particle.

Zhou [19] experimentally investigated the effects of acoustical parameters, nanofluid concentration and fluid subcooling on boiling heat transfer characteristics of a copper–acetone nanofluid. The results showed that the presence of the copper nanoparticles did not affect the dependence of the heat transfer on the acoustic cavities and fluid subcooling. Without an acoustic field, the boiling heat transfer of the nanofluid was reduced. In contrast with the experimental results of Das et al. [3,4], in this study the pool boiling heat transfer was not reduced with increasing nanofluid concentrations. With an acoustic field generated to the nanofluid, the boiling heat transfer was enhanced and the boiling hysteresis disappeared. The enhancement became obvious with increasing fluid subcooling, sound source intensity, and nanoparticle concentration.

5. Convective heat transfer

The natural convection of fluid small-particles suspensions has been used in many applications in the chemical industry, food industry and also in solar collectors [20].

Comparatively, the natural convection of suspensions is different from that of pure fluids. The natural convection of a suspension is driven by the unstable density distribution of liquid due to temperature differences and the distribution of the particle concentration due to the sedimentation [21]. A few studies have reported the natural convection of nanofluids with no, or very little, sedimentation.

Putra et al. [22] presented the experimental observations on the natural convection of two oxide (Al_2O_3 and CuO)–water based nanofluids inside a horizontal cylinder heated from one end and cooled from the other. The dependence of parameters such as particle concentration, particle material and geometry of the containing cylinder were investigated at steady-state conditions. Different from the natural convection of common suspensions, the nature of convection of nanofluids was free from particle concentration gradients and the stratification concentration layers absent. At the same aspect ratio (length to diameter), the natural convective heat transfer of nanofluids was lower than that of the base fluid. However, the natural convective heat transfer of nanofluids deteriorated with increasing particle concentration, aspect ratio of cylinder, and particle density. Even when the particle size of CuO was smaller than that of Al_2O_3, the deterioration in heat transfer was greater. This is because the particle density of CuO is higher than Al_2O_3.

Due to the absence of experimental data on the natural convection of nanofluids, Khanafer et al. [23] developed an analytical model to determine the natural convective heat transfer of nanofluids. The nanofluid in the enclosure was assumed to be in single phase, that is both the fluid and particles are in thermal equilibrium and flow at the same velocity. The effect of suspended nanoparticles on the buoyancy-driven heat transfer process was analyzed. It was illustrated that the heat transfer rate increased as the particle volume fraction increased at any given Grashof number.

Kim et al. [24] proposed an analytical investigation to describe the natural convective heat transfer of nanofluids by introducing a new factor f which included the effect of the ratio of thermal conductivity of nanoparticles to that of the base fluid, the shape factor of the particles, the volume fraction of nanoparticles, the ratio of density of nanoparticles to that of the base fluid and the ratio of heat capacity based on the volume of nanoparticles to that of the base fluid. The results showed that the heat transfer coefficients of nanofluid increased with increasing particle volume fraction. With respect to the particle volume fraction, as the heat capacity and density of nanoparticles increased and the shape factor and the thermal conductivity decreased, the convective motion set in easily [24].

However, it is unclear why the results from the analytical approach of Kim and Khanafer were contrary to the experimental results of Putra, the reasons possibly being dependent on the assumptions of the models.

The addition of particles into heat transfer medias has been known for a long time as one of the passive techniques for enhancing heat transfer. Compared with the heat transfer enhancement technique by using suspended millimeter- or micrometer-sized particles. The use of suspended nanoparticles have been more attractive. This is because nanoparticles are ultra-fine and usually used at low particle concentrations. Therefore, they are free from sedimentation that may clog the flow channel. They are also expected to cause little or no penalty in pressure drop. Before applying nanofluids in practical applications, studies on heat transfer and flow characteristics are needed.

Xuan and Roetzel [25] derived some correlations for predicting the convective heat transfer of nanofluids using two approaches. The first approach treated the nanofluids as a single phase fluid and the other as a solid–liquid mixture. The derived correlations

explained that the mechanism of heat transfer enhancement of nanofluids depended on the increasing thermal conductivity of the suspension and the chaotic movement of particles that accelerate the energy exchange process in the fluid. However, there is still a lack of experimental investigation to validate this model.

Afterwards, Xuan and Li [26] presented an experimental investigation on the convective heat transfer and flow feature of nanofluids. In their experiments, a Cu–water nanofluid was used with the particle concentrations varying between 0.3 and 2% volume fraction and the flows being turbulent in a straight tube. The results indicated that the suspended nanoparticles enhanced the heat transfer of the base fluid, and the convective heat transfer coefficients of the nanofluids increased with increasing flow velocity and particle concentration. The greater heat transfer enhancement was found to be more than 39% at 2% particle volume fraction. Furthermore, nanofluids caused no significant improvement in pressure drop.

6. Conclusions

This paper presents recent developments in research on the heat transfer of nanofluids. From the review of open literature, the following conclusions can be drawn:

1. Nanofluids containing small amounts of nanoparticles have substantially higher thermal conductivity than those of base fluids. The thermal conductivity enhancement of nanofluids depends on the particle volume fraction, size and shape of nanoparticles, type of base fluid and nanoparticles, pH value of nanofluids and type of particle coating.
2. It is still not clear which is the best model to use for the thermal conductivity of nanofluids. Therefore it requires further investigation.
3. The natural convective heat transfer of nanofluids is different from that of the common suspensions in that the particles concentration gradient is absent [22]. The conclusions from experimental and analytical investigations are in disagreement. From analytical investigation, the natural convective heat transfer of nanofluids increases as particle volume fraction and density increase, which is opposite to experimental results.
4. For high heat flux, the experimental results on pool boiling heat transfer indicated that the addition of nanoparticles into the base fluids did not enhance heat transfer. However, the critical heat flux of the nanofluid was dramatically increased. This revealed that nanofluids may be suitable for cooling at high heat flux applications.
5. The suspended nanoparticles remarkably increased the forced convective heat transfer performance of the base fluid. At the same Reynolds number, the heat transfer of the nanofluid increased with the particle volume fraction.

Since nanotechnology is able to produce particles in nanometer size, the suspensions of these particles in conventional fluids have created a new type of heat transfer fluid. Nanofluid has become an innovative idea for thermal engineering, although many questions remain unanswered and need researching. Theoretical and experimental research, both on microscale and macroscale are needed in order to clarify the causes of the enhancement of heat transfer, which would be of help in understanding the transport of nanofluids.

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